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High Energy Ion Analyzer for Laser-Produced Plasma Studies

R. DECOSTE

University of Maryland
College Park, Maryland

AND

B. H. RIPIN

Laser Plasma Branch
Plasma Physics Division

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NAVAL RESEARCH LABORATORY
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A simple electrostatic deflection multi-channel time-of-flight ion analyzer optimized to study high energy ion species from laser-produced plasmas is described. For this application moderate species and energy resolution over a wide dynamic energy range is desirable. A dynamic energy range from 1 to 1000 keV per unit charge is achieved with a 20 kV power supply. Design considerations are presented together with some typical experimental results.

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HIGH ENERGY ION ANALYZER FOR LASER-PRODUCED PLASMA STUDIES

INTRODUCTION

Recent experiments[1] on laser-produced plasmas have shown that ions with energies in excess of 100 keV are produced when a high irradiance laser pulse is focused onto a solid target. These ions can carry away an important fraction of the laser energy absorbed by the plasma. Therefore, more detailed measurements on the energy distribution and charge state of these ions is of primary interest to laser fusion.

Other electrostatic analyzers currently used to diagnose laser-produced plasmas are of the capacitor like type.[2-5] Ions both enter and leave the analyzer through the same plate and several detectors can be accommodated simultaneously. This is efficient for data collection and good energy and species resolution can be achieved. However, for a certain energy per unit charge E/Z and a voltage V between the plates, the ratio (E/Z)/V is typically around 2. High voltage are therefore required to deflect high energy ions and an upper energy limit is typically 100 keV per unit charge.

Here an analyzer configuration is described where a (E/Z)/V ratio around 50 is easily achievable, thereby extending the energy range up to a few MeV/Z. The dynamic range and energy and species resolution are also quite suitable for laser-produced plasma analysis. In this analyzer the ions are first deflected by an electric field perpendicular to their incident velocity. The ions are then collected by several detectors some distance away from the electric field region in a plane parallel to the electric field. Each of the detectors is followed in time to give the time-of-flight and, therefore, velocity of the

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detected ions. Both the design and construction of this system are simpler than most magnetic analyzers[6,7] and Thompson parabola.[8] The analyzer may also be used in the electrodynamic mode if desired.[9] Design considerations for this analyzer and typical results are described below.

PARTICLE DYNAMICS

The schematic of the analyzer is shown in Fig. 1. The z-axis of the coordinate system is between the center of the ion source and the entrance slit of the analyzer. The analyzing electric field is assumed uniform between the parallel plates and the ions are collected at $z = \ell$, $\ell = \ell_1 + \ell_2$ in a plane parallel to the electric field. For an ion of charge to mass ratio q/m having an initial velocity $\underline{v} = v_o\hat{z}$ at $z = -L$ the equations of motion in the electric field region are, in the z direction

$$\ddot{z} = 0 \tag{1}$$

and in the x direction

$$\ddot{x} = \frac{q}{m}\frac{V}{d}, \tag{2}$$

where V is the potential between the plates separated by a distance d. Note that the ion motion along the initial direction is not affected by the applied field and therefore the time-of-flight to the detectors in the $z = \ell$ plane gives the true initial velocity. Integrating Eqs. (1) and (2) and applying the initial conditions at $t = 0$, $z = x = \dot{x} = 0$, $\dot{z} = v_o$, we obtain at $z = \ell_1$,

$$x_1 = \frac{1}{2}\frac{q}{m}\frac{V}{d}\frac{\ell_1^2}{v_o^2}, \tag{3}$$

$$\dot{x}_1 = \frac{q}{m}\frac{V}{d}\frac{\ell_1}{v_o}. \tag{4}$$

The ions drift freely between this point and the detectors at $z = \ell$. Therefore, at $z = \ell$, the deflection from the z-axis is

$$x_2 = (\tfrac{1}{2}\ell_1^2 + \ell_1 \ell_2) \frac{q}{m} \frac{V}{d} \frac{1}{v_o^2} \quad . \tag{5}$$

The ion's time-of-flight from the source to detector is

$$t = \frac{L + \ell}{v_o} \quad . \tag{6}$$

Equations (5) and (6) can be solved to yield the ion's atomic mass to charge ratio A/Z,

$$\frac{A}{Z} = \frac{e}{m_p} (\tfrac{1}{2}\ell_1^2 + \ell_1 \ell_2) \frac{V}{d} \frac{t^2}{(L + \ell)^2} \frac{1}{x_2} \tag{7}$$

and ion's energy ($E = \frac{1}{2}mv_o^2$) per unit charge E/Z,

$$\frac{E}{Z} = \tfrac{1}{2}e(\tfrac{1}{2}\ell_1^2 + \ell_1 \ell_2) \frac{V}{d} \frac{1}{x_2} \tag{8}$$

in terms of the electron charge e and proton mass m_p.

ENERGY AND A/Z RESOLUTION

The theoretical energy resolution of the analyzer is

$$\frac{\Delta E}{E} = \frac{\Delta x_2}{x_2} \quad . \tag{9}$$

Likewise, the A/Z resolution is

$$\left(\frac{\Delta A/Z}{A/Z}\right)^2 = \left(\frac{2\Delta t_\tau}{t}\right)^2 + \left(\frac{2\Delta L}{L + \ell}\right)^2 + \left(\frac{\Delta x_2}{x_2}\right)^2 . \tag{10}$$

Here, Δt_τ can be taken to be the characteristic duration of the ion source, ΔL to be the characteristic length of the ion source and

Δx_2 to be the finite dimensions of the exit slit in the x direction. It is assumed that the initial thickness of the ion beam determined by the entrance slit plus the spread of the beam within the analyzer is less than the width of the corresponding exit slit. The spread of the beam could be due to poor beam collimation or space charge forces discussed in the next section.

Typical values of laser-produced plasmas of interest are $\Delta t \simeq 10^{-10}$ sec, $t \simeq 10^{-7}$ sec, $\Delta L \simeq 10^{-2}$ cm, $L \simeq 10^{-2}$ cm and for the analyzer described in a later section $\Delta x_2/x_2 = 0.1$. Therefore, the main contribution to both the energy and mass resolution is the finite dimension of the exit slits, i.e., the resolution R_τ is

$$R_\tau = \frac{\Delta A/Z}{A/Z} \simeq \frac{\Delta E}{E} = \frac{\Delta x_2}{x_2} \quad . \tag{11}$$

In our case R_τ was chosen to be 10% for each channel in order to optimize the wide dynamic energy range of the analyzer. For more specialized application $R_\tau \simeq 3\%$ could be easily achieved.

The resolution can also be checked experimentally using Eq. (7) for the A/Z resolution and $E = \frac{1}{2} m(L + \ell/t)^2$ for the energy resolution. We obtain for the experimental resolution

$$R_x = \frac{\Delta E}{E} = \frac{\Delta A/Z}{A/Z} = \frac{2\Delta t_x}{t} \quad , \tag{12}$$

where now Δt_x is associated with the pulse width for each species recorded on oscilloscope traces. The voltage variation $\Delta V/V$ during the ion deflection and the characteristic length variation $\Delta L/L$ are negligible. Errors in determination of parameters introduce uncertainty in the energy and A/Z determination but no resolution losses.

SPACE CHARGE FORCES

We have considered only the dynamics of a single ion up to this point. The finite ion density effects within the analyzer are now addressed. The initial thickness of the ion beam in the analyzer is determined by the width of the entrance slit. The entrance slit width must be less than the Debye length of the impinging plasma ($\lambda_D = v_{the}/\omega_{pe}$, where $v_{the}^2 = kT_e/m_e$, $\omega_{pe}^2 = ne^2/\varepsilon_o m_e$) so that the electrons can be stripped from the ions upon entering the analyzer. For the case $\ell \ll L$, the divergence of the ion beam within the analyzer can be neglected. However, the space charge expansion due to the self-electric field of the beam imposes some limitations on the analyzer parameters.

We consider a sheet beam of initial thickness d_o and initial current density j which is the sum of partial beams with current density j_i associated to each ion species. We assume that the spread of each individual beam is given by the sum of the partial beams since the total entering current density is present over a fraction of the distance ℓ. Therefore, if one of the partial beams is to pass entirely through its related exit aperture of width d_2, the following inequality must be satisfied.[10,11]

$$\sum_i \left(\frac{Z}{A}\right)_i j_i \leq \frac{2\varepsilon_o m_p}{e}\left(\frac{d_2}{d_o} - 1\right)\frac{1}{\ell^2} v_o^3. \qquad (13)$$

With too large an entrance slit the output intensity saturates, the input and output intensities lose proportionality and the instrument resolution is degraded. Equation (13) is indeed an underestimate of the maximum current densities allowed in the analyzer. But since most of the transverse impulse is given to the ions within a short distance behind the entrance slit this approximation is preferred to considering completely separated partial beams within the analyzer.

The width of the beam must also satisfy a similar equation with d_2/d_o replaced by h_2/h_o where h_2 and h_o are respectively the exit and entrance slit height. In this case Eq. (13) is also an underestimate. Some examples of maximum output voltage into 50 Ω from a detector are given in the next section.

ANALYZER DESIGN

The analyzer was basically designed to separate ion species of C and H from laser-produced plasmas containing these elements over an energy range from 1 keV to 1000 keV per unit charge with 10% energy and A/Z resolution. Figure 2 shows some design details of the analyzer.

The electric field is defined by the two condenser plates separation, i.e., V/d. With a length and width to separation ratio = 5, non uniformity of the field due to end effects can be neglected. With ℓ_1 = 10 cm, ℓ_2 = 20 cm and d = 2 cm the (E/Z)/V ratio is 35 for the most energetic E/Z channel, i.e., x_2 = 2 cm.

The entrance slit is 0.1 cm wide by 2 cm high. The aspect ratio for each of the 6 exit slits is $d_2/x_2 = \Delta x_2/x_2 = 0.1$. According to Eq. (11), this limits the energy and A/Z resolution to 10%. The height h_2 of the exit slit is 8 cm which gives $h_2/h_o = 4$. The center of the first and last slit is respectively 2 and 8 from the analyzer axis. This restricts the E/Z range per shot to four to one. In a later analyzer version, the energy range per shot has been increased to 14 to one by increasing ℓ_2 from 20 to 25 cm and adding a few more slits to the collector plate. In this second version the (E/Z)/V ratio was also increased to 70.

The ion detector used behind each slit is a planar copper electrode etched on a printed circuit board. Each detector is connected by coaxial cable to a biasing circuit to repel secondary electrons and to a 50 Ω load. The output signal is amplified by 35 dB into 50 Ω with noise level around 15 μV and frequency response 10 kHz < f < 500 MHz using 3 cascaded chip amplifiers from Avankek's GPD series per channel. In the analyzer described above the slit height of the lowest E/Z channel is the limiting parameter ($h_2/h_o = 4$) on the maximum current allowed in the analyzer due to space charge forces (Eq. 13). The output voltage limitation for this detector is plotted in Fig. 3 as a function of the beam energy for three different situations. For a single 1 keV C_{12}^{+1} beam in the analyzer the dynamic range per channel is then approximately one order-of-magnitude and is limited by the noise level and space charge forces. For a 5 keV C_{12}^{+1} beam the output dynamic range is already increased to two orders-of-magnitude.

The tube in front of the entrance slit is used as a waveguide beyond cutoff ($\leq$ 1 GHz) to reduce the low frequency electromagnetic noise produced by the laser-plasma interaction. The whole system should be under a vacuum of at least 10^{-5} torr to reduce any atomic processes with the ambient gas between the ion source and detector.

RESULTS

In the example shown below, a polethylene $[(CH_2)_n]$ planar target was irradiated by a focussed Nd-glass laser (1.06 μ) pulse of 100 psec duration and 26 J energy. The analyzer axis was 35^0 with respect to the target normal and the analyzer entrance slit was 130 cm from the target.

Figure 4 shows oscilloscope traces recorded from 5 channels of the analyzer on a typical shot. The reference time t = 0 is given by the onset of the electromagnetic noise picked up by the ion detectors and amplified. Using Eq. (12), the width of the peaks yields an experimental analyzer resolution in agreement with the theoretical resolution given by Eq. (11). The amplitude of the peaks are typically a few mV. The identification of each peak as to ion species is made using Eq. (7). Each voltage pulse height V_o is then converted to an ion flux J according to

$$J \alpha \frac{V_o}{Z + \gamma} \tag{14}$$

where γ is the secondary electron emission coefficient. Typical results are shown on Fig. 5. The continuous lines are smooth fits through the points.

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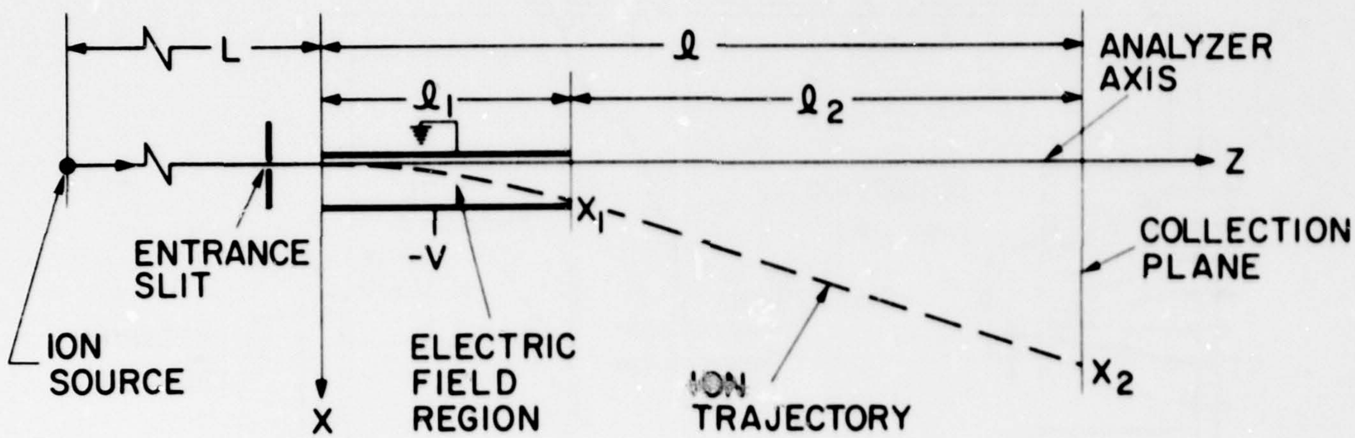

Fig. 1 — Schematic diagram of high energy electrostatic analyzer

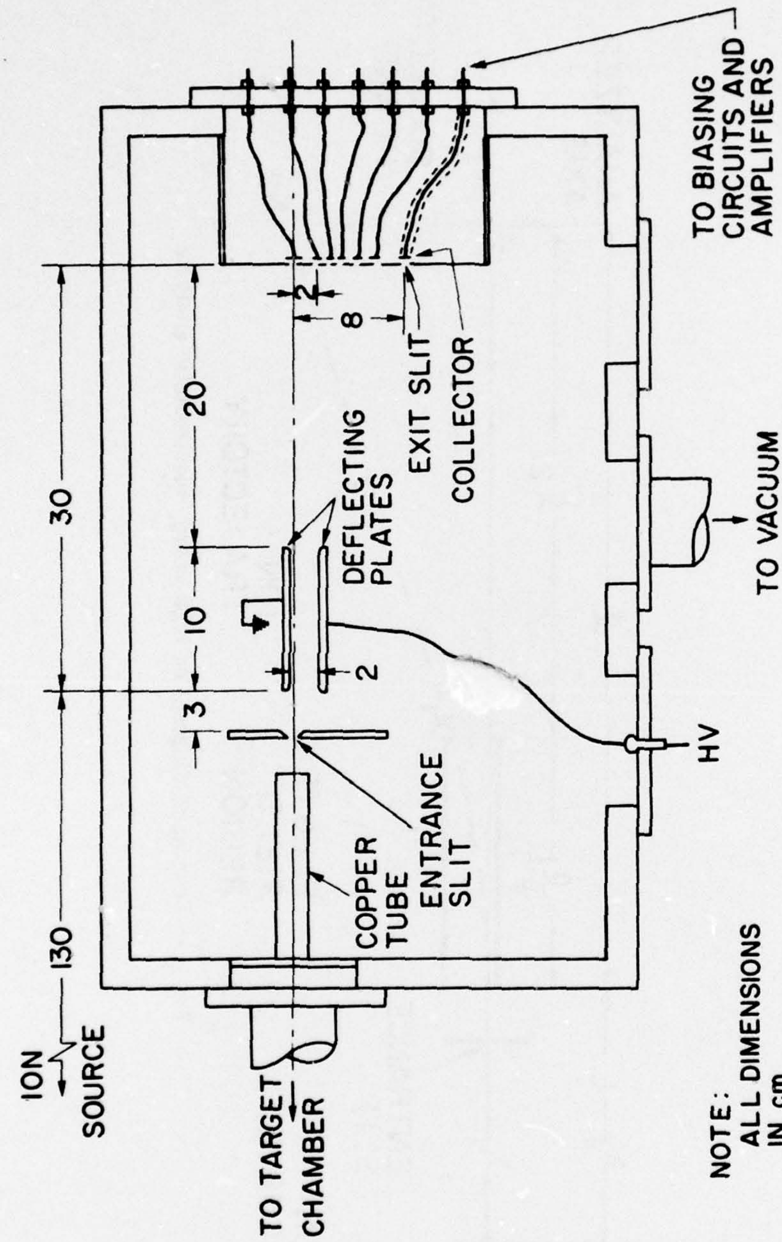

Fig. 2 — High energy ion analyzer

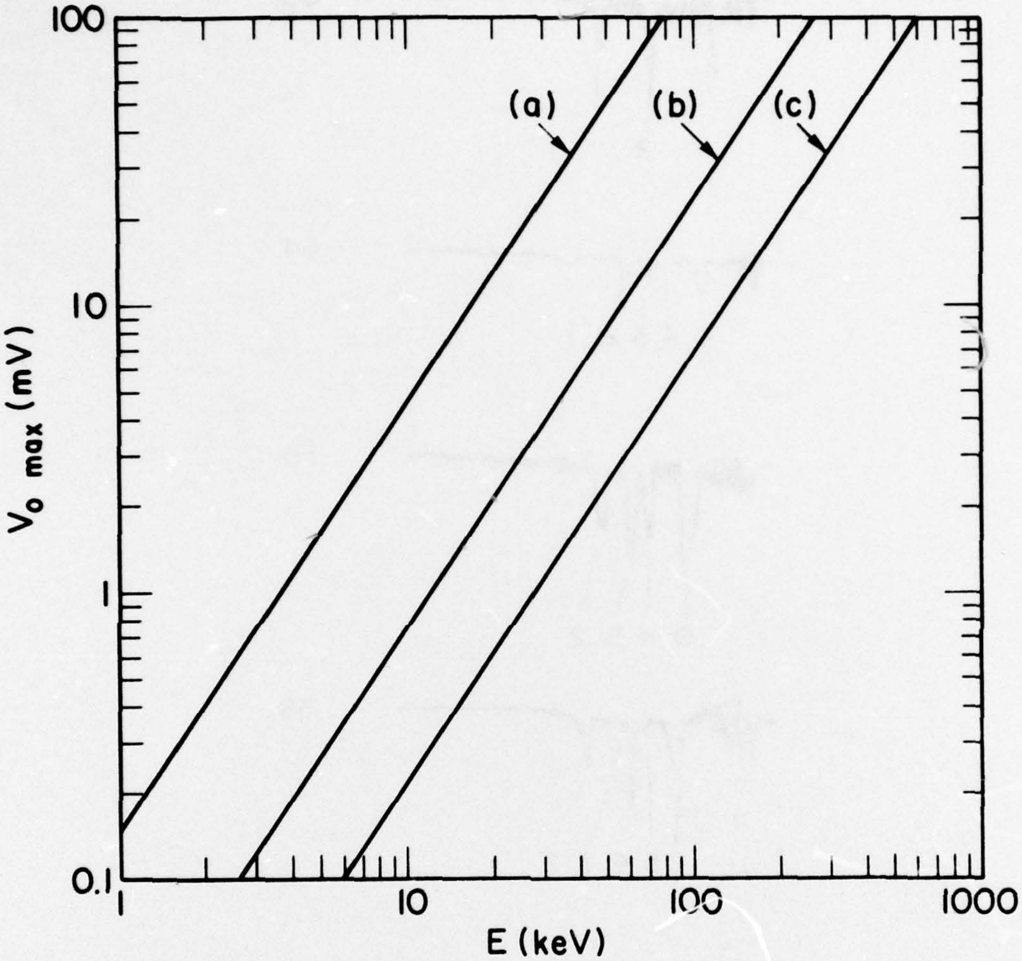

Fig. 3 — Output voltage limitation into 50 Ω due to space charge forces versus ion energy: (a) single C_{12}^{+1} beam in the analyzer; (b) single C_{12}^{+6} beam; (c) mixture of carbon species with equal partial current densities.

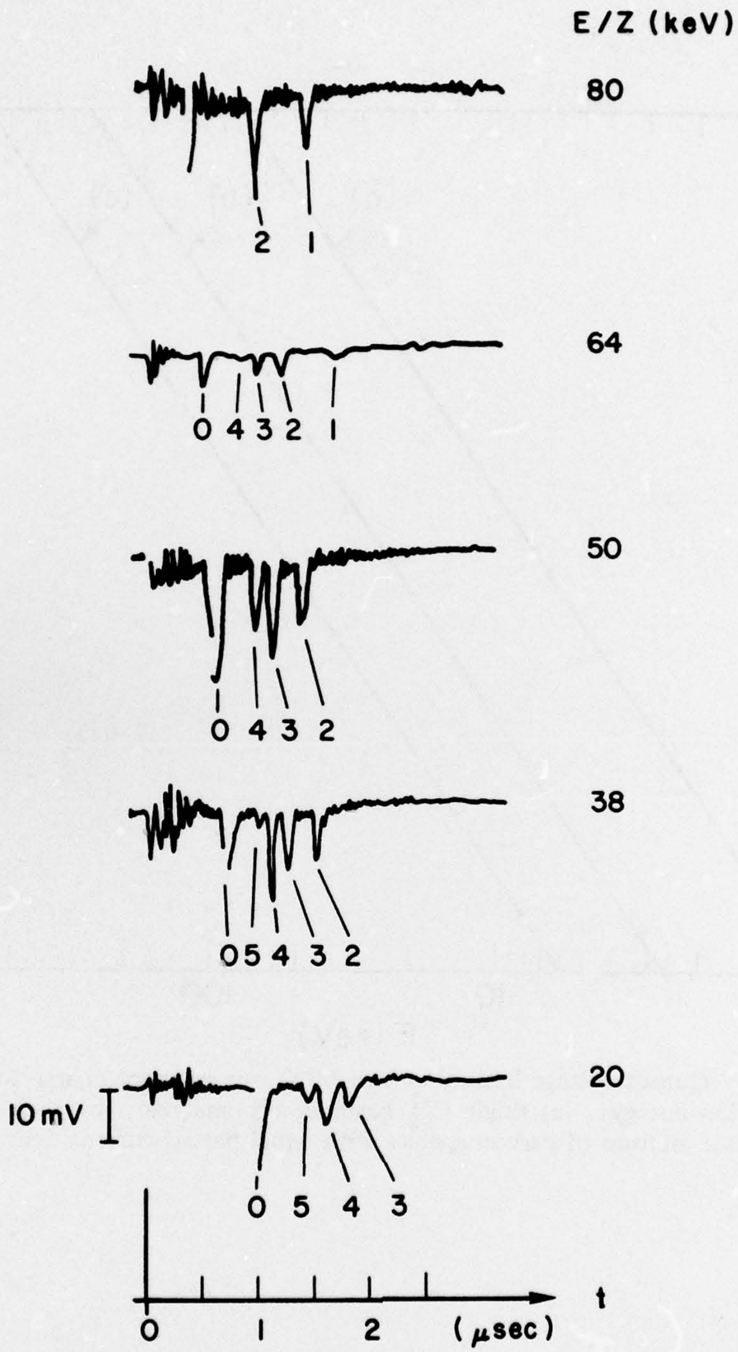

Fig. 4 — Oscilloscope traces of 5 analyzer channels. The numbers identify the following species: 1:C^{+1}, 2:C^{+3}, 3:C^{+3}, 4:C^{+4}, 5:C^{+5}, 0:H^{+1}.

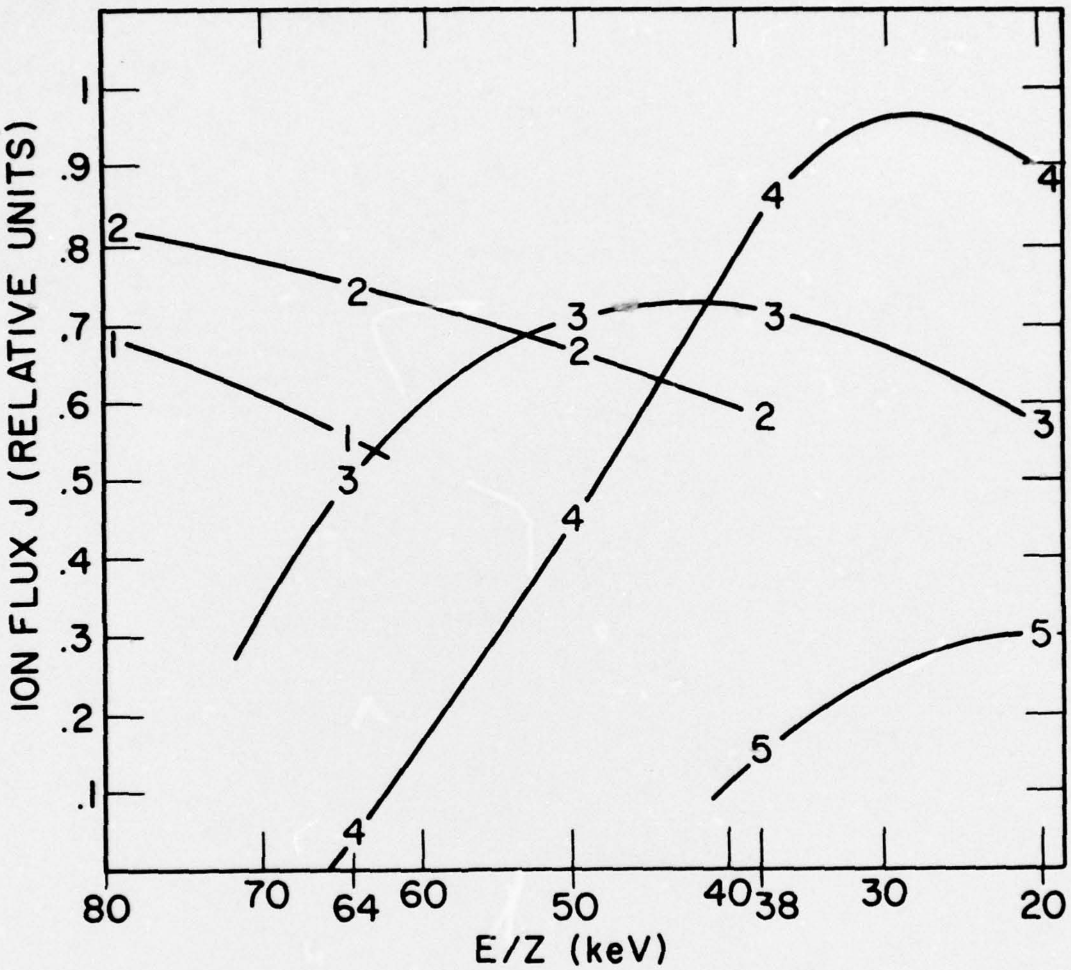

Fig. 5 — Ion spectra from a laser produced plasma. The numbers represent C_{12}^{+Z} charge species. Laser parameters: 26 J in 100 psec at 1.06 μ